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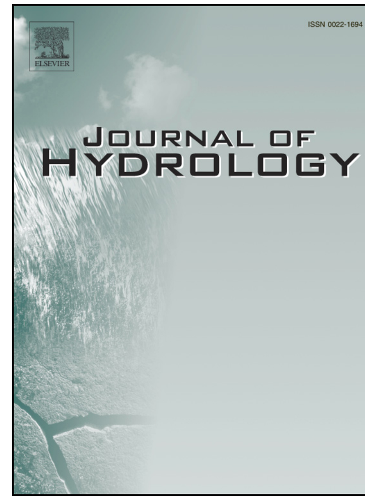

Research papers

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Validation of 2D flood models with insurance claims

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Abstract. Flood impact modelling requires reliable models for the simulation of flood processes. In recent years, flood inundation models have been remarkably improved and widely used for flood hazard simulation, flood exposure and loss analyses. In this study, we validate a 2D inundation model for the purpose of flood exposure analysis at the river reach scale. We validate the BASEMENT simulation model with insurance claims using conventional validation metrics. The flood model is established on the basis of available topographic data in a high spatial resolution for four test cases. The validation metrics were calculated with two different datasets; a dataset of event documentations reporting flooded areas and a dataset of insurance claims. The model fit relating to insurance claims is in three out of four test cases slightly lower than the model fit computed on the basis of the observed inundation areas. This comparison between two independent validation data sets suggests that validation metrics using insurance claims can be compared to conventional validation data, such as the flooded area. However, a validation on the basis of insurance claims might be more conservative in cases where model errors are more pronounced in areas with a high density of values at risk.

1 Introduction

Floods are one of the most damaging natural hazards, accounting for a majority of all economic losses from natural events worldwide (UNISDR 2015). Managing flood risk requires knowledge about the hazardous processes and about flood impacts. In recent years, flood inundation models have been remarkably improved and widely used for flood hazard simulation, flood exposure and flood loss analyses. A variety of models exist for different purposes and scales, reaching from global scale inundation models (Pappenberger et al. 2012, Ward et al. 2013, Sampson et al. 2015) to continental (Trigg et al. 2016), national (Merz et al. 2008) and finally regional and local scale models (Fewtrell et al. 2011, Neal et al. 2011, Pedrozo-Acuña et al. 2012, Almeida et al. 2016, Garrote et al. 2016). Another increasing use of flood inundation models is the coupling of flood models with hydrologic and hydrometeorologic models within a model cascade or a coupled component modelling framework at the river basin scale (e.g., Biancamaria et al. 2009, Falter et al. 2015, Zhu et al. 2016, Felder et al. 2017). Thus, a variety of inundation models exist for different purposes (e.g., Horritt and Bates 2001a, Hunter et al. 2007, Chatterjee et al. 2008, Bates et al. 2010, Crispino et al. 2015, Courty et al. 2017). Developers are validating the models with a broad set of validation techniques and data. Model validation here is defined after Hunter et al. (2007) as the "process of demonstrating that a given site-specific model is capable of making accurate predictions, defined with respect to the application in mind, for periods outside a calibration period". If the accuracy and predictive capability in the validation period is proven to lie within an acceptable limit for a particular practical purpose, it is defined as being validated. Depending on the purpose of the model used and the available data, the validation methods vary remarkably. In 1D simulation frameworks, hydraulic models have been calibrated and validated with observed water levels at specific locations (Horritt and Bates 2002, Mark et al. 2004, Pappenberger et al. 2005, Hunter et al. 2007, Felder et al. 2017). However, with the development of 2D flood inundation models, spatially explicit model performance measures have been proposed and used for model validation. In many cases this is done by comparing the simulated inundation areas with observed ones as shown by Woodhead et al. (2007). Most likely, the main data used in the validation of inundation models is observation data of the wet/dry boundary. This leads to the comparison between modelled and observed inundation areas. Other validation data are aerial images and observed flood maps delineated thereof or satellite-based remote sensing data. Bates et al. (1997) describe a procedure for validating inundation models with remote sensing data. Especially synthetic aperture radar data have recently been used for calibration and validation (Horritt 2000, Horritt et al. 2007, Mason et al. 2009, Pappenberger et al. 2007a, Tarpanelli et al. 2013). In contrast, Neal et al. (2009) and Savage et al. (2016) compared inundation models with a large set of water level measurements in a study area. This is probably the most reliable validation data (Segura-Beltrán et al. 2016). Furthermore, inundation models are also validated against stage-discharge relationships or time to peak (Horritt and Bates 2002). The latter is less often used if the main purpose of the inundation model is to provide the basis for flood loss analyses. For evaluating newly developed models, a benchmark test against established models or models that represent an industry standard is sometimes done (Neal et al. 2012a). The comparison of the flooded areas computed by different models is shown in several studies (Horritt and Bates 2001a, Horritt and Bates 2002, Tayefi et al. 2007, Chatterjee et al. 2008, Fewtrell et al. 2008, Castellarin et al. 2009, Neal et al. 2012a, Neal et al. 2012b, Crispino et al. 2015, Trigg et al. 2016, Vozinaki et al. 2016, Lavoie et al. 2017). However, the main limiting factor for validating inundation models is often the lack of validation data (Neal et al. 2012a).

Beside model validation, the analyses of uncertainties or the sensitivities against model parameters are a fundamental step in model development (Pappenberger et al. 2006, Jakeman et al. 2006, Ratto et al. 2012, Freer et al. 2013, Pianosi et al. 2016, Teng et al. 2017). In sensitivity analysis, one focus is on the representation of the topography, especially the spatial resolution (Horritt and Bates 2001b, Cook and Merwade 2009, Dottori et al. 2013, Savage et al. 2015, Savage et al. 2016). Probabilistic models are able to incorporate a number of model runs with different parameterizations and different boundary conditions. Dottori et al. (2013) state that deterministic models and very high spatial resolution are potentially misleading as they could induce overconfidence derived from their spuriously precise results. This in turn may lead to wrong decisions in flood risk management. Thus, the choice of the modelling strategy depends on the main purpose of the study, the model complexity, the needed computational resources, and the available topographic data (di Baldassare et al. 2010, Dottori et al. 2013, Jonkman 2013, Refsgaard et al. 2016). A key point in the reliability of flood inundation models is the ability to represent flood protection measures (Merwade et al. 2008b, Neal et al. 2012b, Ward et al. 2013). On the reach scale, the inability to accurately represent river morphology is a disadvantage of raster based models. The increase in spatial resolution has a negative effect on the needed computing resources (Neal et al. 2012b, Savage et al. 2015). Solutions for dealing with this trade-off between spatial resolution and computing power are, for example, the use of subgrid approaches (i.e., modelling the flow in the river channel in 1D combined with floodplain routing in 2D) as exemplarily described by Neal et al. (2012b), the coupling of 1D and 2D simulation models (Vozinaki et al. 2016), or the use of nesting approaches as shown by Bermúdez et al. (2017). The latter nested a local scale flood inundation model based on irregular meshes into a basin scale model based on regular grids. A third group of models dealing with this topic is the simulation based on irregular meshes. These can have a high spatial resolution in the river channel and a coarser resolution in the floodplain (Horritt and Bates 2001a). Thus, these models are able to accurately represent river morphology and geometry. This includes the consideration of flood protection measures which is required for predicting flood patterns satisfyingly (Fewtrell et al. 2011). Consequently, the accurate consideration of flood protection measures must also be valid from the viewpoint of flood loss analyses as they increasingly consider single buildings (Zischg et al. 2013, Fuchs et al. 2015, Röthlisberger et al. 2017). However, 2D inundation models are often evaluated regarding the ability to accurately predicting flooded areas. In many cases, the flooded areas predicted by the model are compared with the observed wet areas of a specific flood event. However, such observations may not be an adequate validation dataset in all cases. Especially for flood exposure and flood risk analyses, a model exhibiting a good overall fit regarding inundated areas in a large floodplain may not necessarily produce good results at locations of particular interest for risk assessment (Pappenberger et al. 2007b). Nevertheless, a method for validating 2D inundation models explicitly used for flood exposure and flood loss analyses has not been presented yet.

Therefore, the main aim of this study is to close this gap by developing a method for validating 2D flood inundation models used in flood exposure analyses. For that matter, the validation data and metrics need to be adapted to that particular purpose. Therefore, we propose alternative data for validating the model, i.e., a dataset of geo-localized insurance claims. Herein, the main question concerns the value of validating a 2D flood model on the basis of loss data rather than on the basis of inundated areas. This question is posed under the hypothesis that a validation based on insurance claims gives different weighting to urbanized areas in comparison to areas without values at risk. An additional question is, how the various validation metrics differ between each other when adopted to insurance claims.

The paper is structured as follows: in the methods chapter we first describe the study areas and the method for setting up the flood model. Following, we present the parameters and the boundary conditions for the model runs. Thereafter, we introduce the validation method and the data used. The results focus on both the performance of the model and the proposed validation method. In the discussions and conclusions, the results are discussed, and recommendations for using insurance claims in the validation of flood models are given.

2 Methods

We tested the validation approach on the basis of test cases for which insurance claims were available. All cases represent a complex flood topology with combined riverine and lake flooding. Two test cases have branching river morphologies. The validation is done by a full set of insurance claims in two test cases and by a sample set of claims in the other two test cases. We compare different metrics for validation of models that are based on binary validation data.

2.1 Study area

The four test cases are located in pre-Alpine areas of Switzerland (Fig. 1). The first two test cases are located in the Canton of Nidwalden. The western test case in the municipality of Stansstad is characterized by the Giesslibach torrent, the eastern part of Buochs and Ennetbürgen by the main river crossing the Canton of Nidwalden, the Engelberger Aa. Both river systems contribute to Lake Lucerne, which is a determining factor for flood risk in both study areas as well. Thus, the flooding is also influenced by lake flooding. The third test case is the floodplain in the city of Thun in the Canton of Bern. Here, the main process is lake flooding with combined riverine flooding downstream. The outflow of Lake Thun is the Aare River flowing through the city of Thun. The Aare River has two branches. During low flow conditions, the lake level is regulated by a weir. The fourth case is the floodplain of the city of Interlaken. This floodplain is a quaternary debris cone of the river Lütschine. The city is located between Lake Brienz (upstream) and Lake Thun (downstream). The Aare River connects the two lakes and is also regulated by two weirs during low flow conditions. Thus, this floodplain is affected by combined riverine and lake flooding. Figure 1 shows the location of the study areas.

2.2 Set up of the flood model

Flood loss analyses usually consist of flood scenarios around and above a river’s discharge capacity. Consequently, the river’s geometry has to be represented as accurately as possible. The river reaches of our case studies have lateral dams. Thus, the flood model has to represent not only the correct area for calculating the river carrying capacity but also the correct geometry. This means that the different heights of the left and right dams should be considered in the flood model. In our research, we are using the 2D inundation model (BASEMENT v2.6) because it is based on flexible irregular meshes and, thus, it allows to represent the river bed in a higher spatial resolution than the floodplains. BASEMENT stands for “Basic Simulation Environment”. The model is developed and maintained by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the ETH Zurich. BASEMENT is described in detail by Vetsch et al. (2017) and has been validated analytically. It has been used for dam breach simulations (Vonwiller et al. 2015, Worni et al. 2012, Volz et al. 2012), in river restoration projects (Berchtold et al. 2012, Fäh et al. 2007a, 2007b, Bertoldi et al. 2014), and for the simulation of flash floods (Radice et al. 2012). The model is freely available and is widely used by consultants for flood risk analyses.

The first step in setting up the inundation model is the generation of the computational mesh. Within a predefined delimitation of the study area, we mapped the upper and lower shorelines of the river reaches and lakes. In the floodplains, only the most important hydraulic structures were represented by break lines. The triangulation was done with the TRIANGLE mesh generator of Shewchuck (2002). This step is part of the pre-processing plug-in implemented in QGIS (BASEmesh, Vetsch et al. 2017). After generating the mesh, we directly attributed the z-coordinates to the nodes by using the local cell values of the digital terrain models. For the test sites in the Canton of Nidwalden we used the digital elevation model SwissALTI^{3D}, produced by the Federal Office of Topography (SWISSTOPO 2013). This terrain model is available for the whole of Switzerland and has a grid resolution of 2 m. The vertical accuracy is expected to be around +/- 0.5 m. For the other study areas, we used a purely Lidar-derived digital elevation model provided by the Canton of Bern (KAWA 2015). This model has a grid resolution of 0.5 m and a vertical accuracy of +/- 0.2 m. For the interpolation of the riverbed, we used surveyed cross sections with a mean distance of 100 m, provided by the Federal Office of Environment (FOEN 2012). We interpolated the riverbed levels between the cross sections by adapting the approaches proposed by Merwade et al. (2008a), Conner and Tonina (2014), and Costabile and Macchione (2015). The points of the cross sections were connected with 3D-polylines and the grid cells in between the cross sections were interpolated on the basis of the mean slope between the cross sections. Finally, we checked if the interpolated grid cells of the riverbed lay below the water surface measured by the Lidar. The terrain model of the riverbed was merged with the terrain model of the floodplain. The bottom of the lake was set to the minimum z-level of the connected river cells. From the merged digital terrain model, we computed a focal statistics raster of the maximum and minimum values within a 3x3 raster cell environment. The merged terrain model was the basis for attributing the z-values to the nodes of the mesh, except for the nodes located on an upper shoreline of the river or a lake and the nodes located within the river channel. The z-values of the nodes representing the upper shorelines were attributed from the maximum focal statistics raster. The nodes within a river channel have been attributed with the z-values of the minimum raster. This leads to a smoothing of the river channel geometry and to a better representation of the river bank, and respectively the lake shorelines. The riverbed morphology is relatively simple since it is in all cases a totally anthropogenically modified river channel with approximately a trapezoidal form. Thus, we do not expect relevant problems arising from the effects of bathymetry interpolation on hydrodynamic results as shown by Conner and Tonina (2014). The roughness parameters (Manning/Strickler values) were delineated from the official guidelines of BWG (2001). We did not calibrate these parameters and no field investigations were made or retrospectively considered in this model setup. The weirs were considered as hydraulic obstacles in the river channel given by their geometries. The mesh has a maximum triangle area of 20 m^2 for river channel elements (50 m^2 in the case studies of Thun and Interlaken) and 100 m^2 for all other elements

(1000 m^2 in case studies of Thun and Interlaken). The case studies of Thun and Interlaken have a coarser spatial resolution because these models are implemented in a model chain for the whole basin of the Aare River upstream of Bern (3000 km^2) and thus are more focused on simulations at the river basin scale (Zischg et al. 2016). An extract of the mesh from the Buochs/Ennetbürgen case study is shown in Fig. 2.

For the upper boundary conditions of the validation runs we used the hydrographs measured during the reference flood event in August 2005. The hydrographs of the lake levels of Lake Lucerne, Lake Thun and Lake Brienz, and the hydrographs of the rivers Engelberger Aa at Buochs and Lütschine at Gsteig were delivered by the Federal Office for Environment FOEN with a temporal resolution of 1 hour. In the Lütschine River, a dam breach occurred abruptly in the early morning of the 23rd of August, 2005. We assumed that not considering the dam breach would lead to unrepresentative results. Thus, the breach of the left lateral dam of the Lütschine River was considered by using two models with the same mesh structure but slightly different Z-values where the dam broke, as similarly shown by Vorogushyn et al. (2010). The first model with the intact dike at the Lütschine River ran until the 23rd of August at 03:00 AM. Water surface elevations and flow velocities were conserved and used as a inputs for the second model with the considered dike breach, in addition with the continuative hydrograph. In contrast, the dike breach in the Engelberger Aa (case study Buochs/Ennetbürgen) is part of a flood corridor and, thus, a spillway. This situation is considered in the model by the dimension of the spillway after the overflow throughout the whole simulation.

2.3 Model validation with insurance claims

In all four case studies, a flood event occurred from the 22nd to 26th of August 2005. Depending on the site, the return period of this flood event was estimated by public authorities to be around 100-200 years. We used this flood event for the validation of the inundation model.

Validation data

If available, georeferenced data about flood-affected buildings and associated losses provide a validation dataset that is best suited for describing the performance of inundation models used for the analyses of exposure and flood losses at the level of the single buildings. If insured, flood losses are being paid out by the insurance company to policyholders affected by a flood event. Due to direct financial interests, the claims are checked by experts and thus an overestimation of the number of cases is not expected. Losses that are smaller than a minimum threshold of re-imbursements are not paid out but are still documented in the claims (franchise of 200 Swiss Francs in Nidwalden for residential buildings and 500-3,000 Swiss Francs for industrial buildings). In a monopoly situation with a mandatory insurance for all house owners, a situation found in most Swiss cantons, the number of claims is very close to the number of affected buildings. Thus, for a settlement affected by a flood, it can be expected that a relevant number of insurance claims should be recorded. The claim records report the date and the amount of damage, as well as the type and address of the affected building. The address can be used for geocoding and, thereby, to localize the losses (Bernet et al. 2017). This results in a point dataset of geo-localized flood losses. The points can then be used to represent hits and non-hits. In a monopoly situation the "non-hits" are also known when the total dataset of insured values is made available by the insurance company. Together, the data provide binary information about which buildings were affected by a flood, and which ones were not, respectively. The access to these datasets is generally heavily restricted due to privacy regulations and due to commercial sensitivities in the case of free markets. In the Canton of Nidwalden, the insurance against natural hazards is mandatory. In this case, the public insurance company delivered anonymized insurance claims of the flood event in 2005 and the anonymized total stock of insured values (as valid per 01 January 2014). The damage data from the Public Insurance Company for Buildings (PICB) of Nidwalden were pre-processed as described in Bernet et al. (2017). During the flood event in August 2005 (period of 21st to 31st), the PICB received 1,238 damage claims in the Canton of Nidwalden. Therefrom, only 26 claims do not include precise coordinates at the building level. 155 claims were rejected, or are still pending. These cases were not considered in the analysis. 206 data points are located within the study area of Stansstad, and 326 within Buochs and Ennetbürgen. Additionally, 95.1 % of more than 1300 portfolio entries (Stansstad more than 450, Buochs and Ennetbürgen more than 800) within the study areas contain reliably localized data.

The buildings within the Canton of Bern are also insured by a PICB. In contrast, their data were not delivered due to privacy restrictions. Thus, the validation in the study areas of Thun and Interlaken has been done with data from the cooperative insurance company "Swiss Mobiliar". These data contain anonymized claim records of building content and business inventory (excluding vehicles), as opposed to damages to buildings in the two case studies in the Canton of Nidwalden. This dataset, as well as the provided anonymized portfolio as per 31 December 2014, does not cover all buildings since the market for content and business inventory in the Canton of Bern is open to all private insurance companies. Thus, for the two case studies in the Canton of Bern, we cannot validate the inundation model with the basic population but only with a sample dataset. 311 damage claims are located in the study area of Thun, and 470 claims are located in the study area of Interlaken. In this study area, only the claims that could be localized at the building level were used for validation, i.e., 147 damage claims were not considered in the analysis because of an uncertain geo-localization.

One problem in attributing the exposure to floods and flow depths to vulnerable objects on a local scale is the spatial representation of the objects. An object represented by a point is probably less exposed than the same object represented by a polygon (e.g., building footprint, Röthlisberger et al. 2017). Thus, the point information from the insurance companies might not adequately represent the location of the building, especially in regards to the exposition of floods near the outlines of the inundation area. Therefore, we aggregated the pointwise damage and portfolio information to the building footprints of the SwissTLM^{3D}, provided by the Federal Office of Topography (SWISSTOPO 2017). Because the portfolio data are valid from 01 January 2014, to 31 December 2014 and the flood event occurred in August 2005, a dissent in the datasets has to be assumed. For this issue, the precise dataset "Buildings and Dwellings statistic" (FSO 2012) from the Federal Statistical Office containing information about the period of construction was intersected with the building footprints as described by Fuchs et al. (2017) and Röthlisberger et al. (2016, 2017). By means of the known period of construction, buildings built after 2005 can be detected and dismissed. However, the construction period is available only for residential buildings. We assume that this removal of the buildings constructed after 2005 from all buildings better represents the situation at the time of the flood event.

In the case of Nidwalden, detailed information about the functionality of all buildings in the study area is given. 28.1 % of all buildings defined as "minor constructions and auxiliary buildings" do not overlay a building footprint polygon and 95.2 % of all such auxiliary buildings within the mapped flood event perimeter are themselves not documented as affected, whereas 77.6 % show at least one entry with the same address but being exposed to the flood in contrary. In practice, the insurance company of the Canton of Nidwalden cumulates the information about losses for multiple buildings (including minor constructions and auxiliary buildings such as garages) from one owner to the home address of the owner. The obvious errors due to this practice are considered by deleting these footprints, as well as building footprint polygons not including any portfolio point. The information about the building purpose allows us to distinguish between residential and non-residential units. In Thun and Interlaken, where such information from the insurance company is lacking, the Buildings and Dwellings statistic is used for this differentiation. In the study areas of Nidwalden 17.8 % of the exploitation information (residential or non-residential) provided by the insurance company is not consistent with the information from the Buildings and Dwellings statistics. Reasons can be found, for instance, in mixed usage within the same building or merged footprint polygons, due to spatial proximity.

The validation based on insurance claims was compared with a conventional validation approach. Namely, we used a second validation dataset, i.e., event documentations of the Cantons of Nidwalden and Bern. These datasets delimit the flooded areas of the flood event in August 2005 and are independent from the insurance claims.

Validation metric

The processed insurance data can be used to validate the model performance of the presented inundation models by adopting different metrics that allow for a spatially explicit application. The most used metrics to compare real and modelled values are i) the model fit measure, also named as the thread score, respectively the F statistics or the critical success index CSI (Bates and deRoo 2000, Horritt and Bates 2002, Tayefi et al. 2007, see eq. 1), and ii) the flood area index FAI (Falter et al. 2013). Hereafter, we use the term "model fit" for the first metric. Other metrics that can be used on these data are accuracy statistics (eq. 2), the bias score (eq. 3), the probability of detection (eq. 4) or hit rate, the false alarm ratio (eq. 5), the probability of false detection or false alarm rate (eq. 6), and the success index (eq. 7). For a detailed description we refer to Bennett et al. (2013). We will compare the model fit with the other validation measures, with a focus on the comparison between the model fit and the FAI (eq. 8). Both metrics are based on the same equation but on different validation datasets. In our case, the model fit is calculated on the basis of specific points in space, whereas the FAI is computed on the basis of areas. Before quantitatively analysing the model performance, a visual performance analysis is done.

The model prediction in terms of the number of exposed building footprint polygons are compared with the observed number of exposed polygons. A building is defined as exposed if its footprint intersects with a mesh element consisting of at least one node with a flow depth greater than 0 m. If the building is correctly predicted as inundated, it counts as a hit. Buildings predicted as dry by the model and observed as inundated, are counted as misses. Correct negatives are buildings that are predicted as dry by the model and are observed as dry in the insurance claims. Buildings predicted as wet by the model but observed as dry in the insurance claims are defined as false alarms.

$$F = \frac{\mathrm{Num}(S_{mod} \cap S_{obs})}{\mathrm{Num}(S_{mod} \cup S_{obs})} \quad (1)$$

S_{mod} is the set of buildings predicted as flooded, and S_{obs} is the set of buildings flooded. Num() denotes the number of members of the set. The following metrics are used for comparison with the model fit (Bennett et al. 2013).

$$Accuracy = \frac{\text{hits + correct negatives}}{\text{total}} \quad (2)$$

$$Bias\ score = \frac{\text{hits +false alarms}}{\text{hits +misses}} \quad (3)$$

$$Probability\ of\ detection\ (hit\ rate) = \frac{\text{hits}}{\text{hits + misses}} \quad (4)$$

$$False\ alarm\ ratio = \frac{\text{false alarms}}{\text{hits + false alarms}} \quad (5)$$

$$Probability\ of\ false\ detection\ (false\ alarm\ rate) = \frac{\text{false alarms}}{\text{correct negatives + false alarms}} \quad (6)$$

$$Success\ index = \frac{1}{2}\left(\frac{\text{hits}}{\text{hits + misses}} + \frac{\text{correct negatives}}{\text{correct negatives + false alarms}}\right) \quad (7)$$

$$FAI = \frac{\text{M1D1}}{\text{M1D1+M1D0+M0D1}} \quad (8)$$

In this equation, M1D1 is the area simulated as flooded and observed as wet, M1D0 is the predicted flooded area but observed as dry in the observation, and M0D1 is the predicted dry area but observed as wet.

3 Results and discussion

In this chapter, the results from the model validation are presented and discussed focussing on the model performance and on the validation metrics. The absolute values used for calculating the validation metrics are shown in Table 1. The values needed for calculating the FAI are shown in Table 2. The values of the validation metrics are shown in Table 3. Regarding the model fit measure (eq. 1) including all types of buildings (see Table 3), only the simulation of Stansstad shows a satisfactory value above 0.7 which is commonly used as a treshold for good performance. In relation to insurance claims, the model runs have a model fit of 0.66 in Buochs/Ennetbürgen, 0.74 in Stansstad, 0.56 in Thun, and 0.47 in Interlaken. Only considering residential buildings which were constructed before the time of the flood event (values in brackets), the model fit measure is considerably higher for Buochs/Ennetbürgen and Stansstad, whereas this is not the case in Thun or Interlaken. This behaviour can be seen for every validation metric, out of the already mentioned model fit measure (eq. 1), the bias score (eq. 3), the hit rate (eq. 4) and the false alarm ratio (eq. 5) in the case of Thun. From now on, only results corresponding to all types of buildings are discussed. A difference in the values of the model fit measure can be found between the case studies with a complete damage and portfolio dataset in Nidwalden (F = 0.66 and 0.74, respectively) and the two case studies in the Canton of Bern, where only a sample dataset was provided (F = 0.56 and 0.47, respectively). It is still an open question whether this influences the validation results, and has to be addressed in the future. The highest accuracy value (eq. 2) can be found in Thun, where more than 90 % of all buildings were predicted correctly with regard to hits (observed and modelled) and correct negatives (not observed and not modelled). In all other study areas, this value ranges from 77 to 79 %.

The bias scores (eq. 3) show, that in Buochs/Ennetbürgen, Stansstad and Thun “false alarms” compared to “misses” are overrepresented, leading to a bias score greater than 1. In these cases, the flood model showed a tendency to overestimate the number of exposed buildings. In Interlaken this relation is inverted and the bias score is below 1. The high amount of misses also influences the hit rate (eq. 4). In Interlaken, in comparison to the other model runs this value is low as well.

In Thun and Interlaken, 33 – 34 % of all modelled events are false alarms (eq. 5, false alarm ratio), which is more than 10 % higher than in all other model regions. In the model region of Stansstad, more than half of all buildings not being observed as exposed to the flood were modelled as exposed (eq. 6, false alarm rate). In Buochs/Ennetbürgen, this is applicable for 24 %, in Interlaken for 13 % and in Thun for 7 %. The metric shown in equation 7 equally weights the ability of the model to correctly detect occurrences and non-occurrences (Bennet et al. 2013). The model run of Stansstad shows the lowest values.

The ratio between the modelled area intersecting the observed area and the union of both (eq. 8, flood area index) is showing the highest scores for Buochs/Ennetbürgen. Depending on whether the modelled river area is included and assumed as an M1D1 area (“hit”), this value again gets even higher (values in brackets, Table 3). Particularly in Thun, the flood area index is enhanced more than 10 %. The corresponding maps are shown in Fig. 3-5.

In all case studies, differences between the modelled floods and the documented inundation areas can be observed. In the case of Buochs/Ennetbürgen, the model run resulted in an underestimation of the inundated area in the northern part of the study area (Fig. 3, left). This can be explained by the fact that a small tributary was neglected, which, according to the event documentation, lead to local flooding. Furthermore, the artificial breach in the lateral dam of the main river is a special invention of the Cantonal engineering administration. The discharge structures are designed in a way that they can overflow without being breached. In case of overflowing, the lee side of the dike is eroded and the excess flow is suddenly guided towards the flood corridor. In contrast to our simulation setup, the overflow was, in reality, withheld for a longer period and suddenly increased after the overflow. Thus, the peak discharge of the excess flow must have been slightly higher in reality than in our simulation. However, the flood corridor was not definitively implemented at the time of the flood and thus losses occurred in this study area. Another area that was underestimated by the model can be found in the case of Stansstad (Fig. 3, right). In the eastern part of the study area, a wider area is predicted as being dry, while documented as being wet according to the event documentation. This underestimation is the result of neglecting sediment transport in the small tributary Gieslibach. In the report of the event documentation, the tributary flooded the left side because the sediment retention basin was filled with sediment and the water consequently flowed also towards the left in contrast to the evidence of the terrain model. Fig. 3 indicates a few of buildings that are located within the flooded areas while, according to the claim data, no damage had been caused during the event. These buildings are either associated with a low vulnerability against flooding or they are located above the water surface elevation at the micro-relief scale. In the case study of Thun (Fig. 4), the model remarkably overestimated the flooded area near the two branches of the Aare River in comparison with the event documentation dataset. However, the insurance dataset shows damages in this area. It is unknown, whether these damages resulted from excess rainfall, groundwater flooding or from riverine flooding. Note that we are not allowed to map single points of the losses in Fig. 4 and Fig. 5 due to privacy reasons. The overestimation near the lake outflow can be explained by micro-scale topographic features not present in the terrain model. The area in the south of Thun is underestimated by the model but mapped in the event documentation. In reality, this area was affected by groundwater flooding and not directly by lake flooding. In Interlaken, the simulation resulted in a remarkable overestimation of the flooding north of the highway due to the dike breach on the Lütschine River (Fig. 5). However, the insurance claims show a considerable number of damages in this area. The model underestimated two weak points along the Lütschine River. The weak point downstream of the dam breach is not considered in the simulation because we used the river topography from 2014 with additional river widening and lateral dams implemented since 2005. However, the underestimation of flooded areas along the Aare River cannot be explained by simple topographical differences between 2014 and 2005. Here, the complex situation with two weirs and a branching river might not be represented with sufficient accuracy. In our model, the weirs are represented only as flow obstacles and not as weirs. This situation needs to be optimized for future work. In summary, most of the false predictions can be explained by micro-topographic structures and changes in the river channel due to flood prevention measures after the flood of 2005. Similar observations were made by Horritt and Bates (2001b), Bates et al. (2003), Fewtrell et al. (2008), Boettle et al. (2011), Dottori et al. (2013), and Almeida et al. (2016). Nevertheless, the results show an acceptable performance even without calibration (Wright et al. 2017), iterative corrections of the mesh (Jakeman et al. 2006), implementation of expert knowledge (Gharari et al. 2014), or the discussion of the uncertainty in the boundary conditions (Pappenberger et al. 2006). However, adapting the computational mesh or the reconstruction of the river geometry as present during the reference flood may result in a better performance. Furthermore, the flood event of 2005 was a remarkable but not extreme flood event. The peak discharge was not substantially higher than the channel carrying capacity. Thus, after Stephens et al. (2014) the validation values should be interpreted as conservative. In this study, we considered a building as exposed if it is affected by mesh nodes with a flow depth greater than 0 m. It remains an open question, if this assumption affects the validation metrics and has to be analysed in future works. The model fit calculated on the basis of the insurance claims data differs from the one based on flooded areas. In Stansstad, the F value is higher than the FAI value. In this case study, claims are located in some areas predicted as wet by the model and observed as dry by the event documentation. In addition, a proportion of the areas predicted as wet but observed as dry do not contain buildings at all. This leads to an F value greater than the FAI value. In contrast, the F value is significantly lower than the FAI value in the other three case studies. Namely, relevant proportions of the areas that the model predicted well are located outside of the urbanized area while the deviations are located within the urbanized areas. In the case study of Interlaken, this most apparent. The model run erroneously predicted a relevant area in the centre of Interlaken as flooded (Fig. 5) that contains a high number of buildings. In contrast, in a relevant proportion of the accurately predicted wet areas, no buildings are located. This case demonstrates that the validation based on insurance claims is only considering points in space that are particularly relevant for flood risk assessment.

4 Conclusions and recommendations

The comparison between two independent validation data sets suggests that validation metrics using insurance claims can generally be compared to conventional validation data, e.g., the flooded area. Although the model fit computed on the basis of insurance claims gives similar results, the values are slightly lower than the ones computed on the basis of the observed inundation areas in three out of four test cases. Hence, it is shown that a model with a good overall fit calculated on the basis of observed inundated areas does not necessarily exhibit a similarly good fit at locations of particular interest for risk assessment. Thus, a validation on the basis of insurance claims might be more conservative in cases where model errors are more pronounced in areas with a high density of values at risk. As insurance portfolios and loss data represent the most relevant target for a validation of flood models used for exposure assessments at the scale of the single buildings, this data can be recommended for validating inundation models.

However, the considered model fit metric based on insurance claim data penalizes both misses and false alarms. When a flood loss analysis aims at capturing the worst case, e.g., for portfolio analysis, the false alarms may have a lower weight, which is considered by the hit rate. the false alarm rate gives higher weights to false alarms but is sensitive to the correct negatives and thus to the delimitation of the study area. In summary, the use of additional validation metrics offers a more reliable base to assess specific aspects of the model performance rather than the model fit measure alone. Insurance claim data allow to calculate most of the binary validation metrics in a spatially explicit manner and, thus, allow to obtain more detailed insights regarding the advantages and the weak points of the selected 2D flood model. Nevertheless, the delimitation of the study area influences the proportion of the number of buildings within and outside the flooded areas and with it some of the described validation metrics.

Nevertheless, the insurance data have to be carefully pre-processed before being using it for model validation. Special attention has to be given to examine whether the construction date of each building corresponds to the date of the reference flood event used for validation. The analysis showed that the removal of buildings constructed after the reference flood event influences the model fit. Another point to consider in pre-processing insurance claim data is to filter out claims associated to surface water flooding, as shown by Bernet et al. (2017) or claims associated with groundwater flooding. This has not been done in this study and should be addressed in future studies. Nevertheless, insurance claims constitute a potential validation dataset because of their consistent and relatively homogeneous records over time. In contrast to flood event documentation data sets, insurance claims are covering also small events and thus these data can remarkably extent the validation data, in general. Still, it remains an open question whether the flooded areas of past events can be reconstructed on the basis of insurance claims data.

Last but not least, the data availability constrained by privacy protection is a critical point. This will likely remain the main limitation of the presented approach. However, the presented validation approach can be adapted to situations where insurance claims are not available, when mapped flooded areas and a building dataset are obtainable. With an overlay between the flooded areas and the buildings' footprints, a binary validation dataset similar to a dataset of insurance claims could be created.

Code and/or data availability. The BASEMENT software is freely available at http://www.basement.ethz.ch. The validation data is under strict privacy rights and unfortunately it cannot be shared. The inundation models used for the validation are available under the creative commons attribution at zenodo.org (https://www.zenodo.org/record/815136#.WUojTlFpxhE), doi:10.5281/zenodo.815136.

Authors' contributions. A. Zischg designed the study. M. Mosimann and A. Zischg prepared the simulation models and made the simulations. M. Mosimann prepared the insurance claims for Thun and Interlaken and computed the validation. D.B. Bernet and V. Röthlisberger processed the insurance data of the Canton of Nidwalden. The manuscript was prepared by A. Zischg with contributions of all co-authors.

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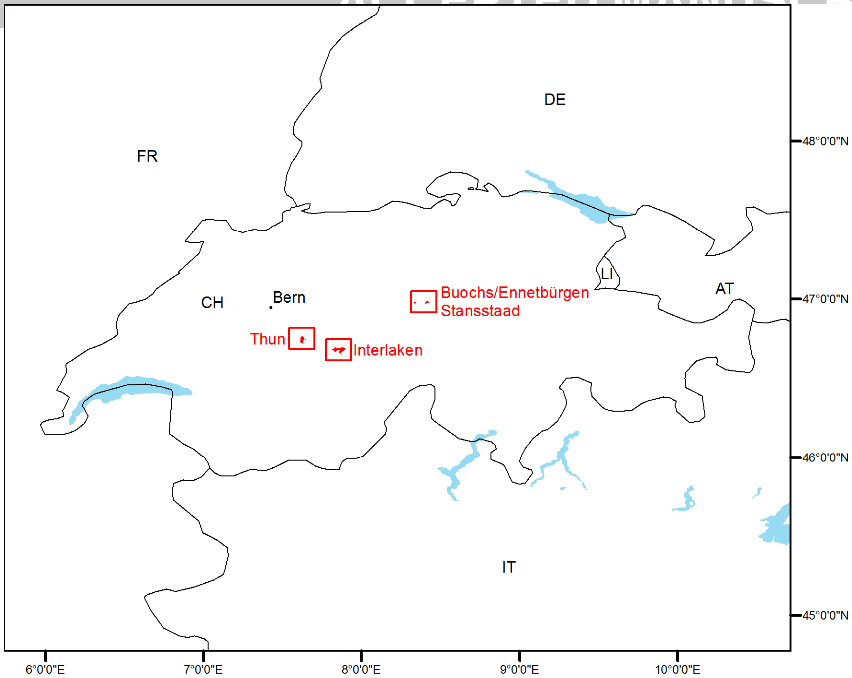

Figure 1: Location of the four study areas.

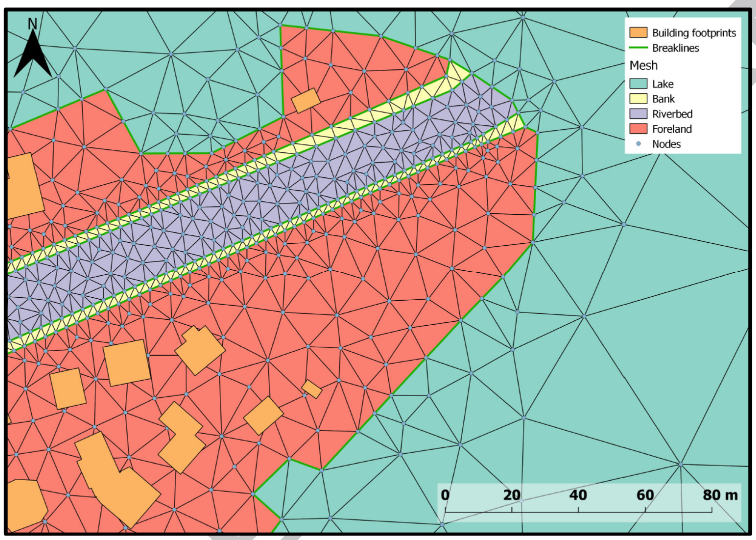

Figure 2: Extract from the computation mesh in the Buochs/Ennetbürgen study area

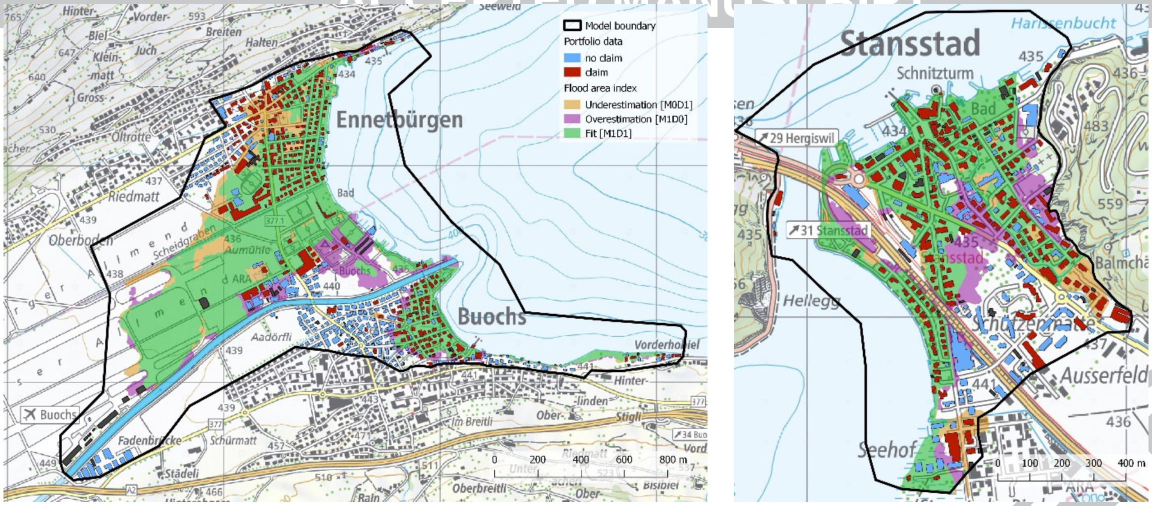

Fig. 3: Map of the simulated inundation areas and insurance claims in Nidwalden. Map sources: SWISSTOPO (background map, reproduced by permission of SWISSTOPO (BA17073), Cantonal insurance Nidwalden (claims), Canton of Nidwalden (event documentation dataset).

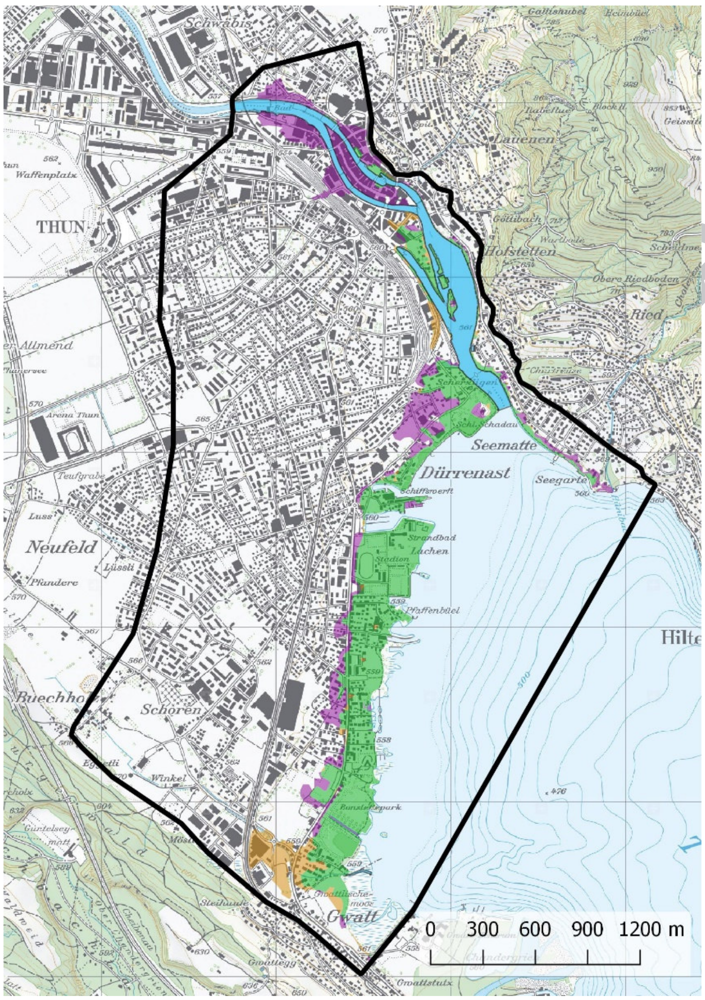

Fig. 4: Map of the simulated inundation areas and comparison with the event documentation data in Thun. The green colour shows the correctly predicted inundated areas, the violet colour shows the overestimation, and the yellow colour shows the underestimation. Map sources: SWISSTOPO (background map, reproduced by permission of SWISSTOPO (BA17073), Canton of Bern (event documentation dataset).

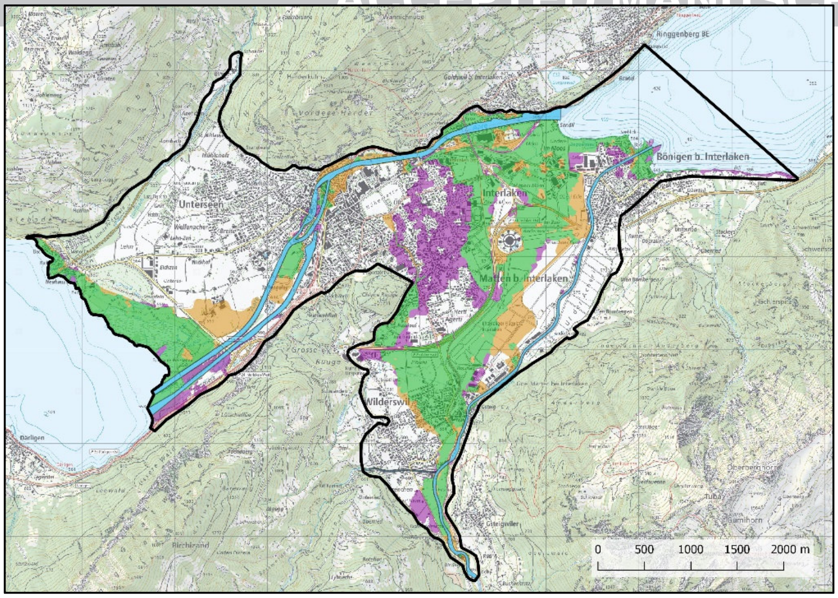

Fig. 5: Map of the simulated inundation areas and comparison with the event documentation data in Interlaken. The green colour shows the correctly predicted inundated areas, the violet colour shows the overestimation, and the yellow colour shows the underestimation. Map sources: SWISSTOPO (background map, reproduced by permission of SWISSTOPO (BA17073), Canton of Bern (event documentation dataset).

Table 1: Absolute values used for calculating the validation metrics of the four test cases (number of buildings). Values in brackets show metrics only considering residential buildings.

value	Buochs / Ennetbürgen	Stansstad	Thun	Interlaken
hits	227 (198)	164 (144)	137 (111)	162 (137)
misses	55 (45)	16 (12)	37 (30)	105 (87)
correct negatives	194 (154)	35 (27)	975 (890)	528 (441)
false alarms	60 (36)	42 (29)	72 (59)	79 (65)

Table 2: Absolute values used for calculating the flood area index FAI of the four test cases (m^2). * Area of river reach included.

value	Buochs / Ennetbürgen	Stansstad	Thun	Interlaken
M1D1	648712 (62823*)	267452	752937 (271528*)	6058312 (679770*)
M1D0	112003	86712	359547	1338693
M0D1	131638	42788	120445	1756338

Table 3: Validation metrics of the four test cases. Values in brackets show metrics only considering residential buildings. * River main channels count as an M1D1 (“hit”), lake areas are always excluded.

validation metric	Buochs / Ennetbürgen	Stansstad	Thun	Interlaken
model fit F	0.66 (0.71)	0.74 (0.78)	0.56 (0.56)	0.47 (0.47)
Accuracy	0.79 (0.81)	0.77 (0.81)	0.91 (0.92)	0.79 (0.79)
Bias score	1.02 (0.96)	1.14 (1.11)	1.20 (1.21)	0.90 (0.90)
Hit rate	0.81 (0.81)	0.91 (0.92)	0.79 (0.79)	0.61 (0.61)
False alarm ratio	0.21 (0.15)	0.20 (0.17)	0.34 (0.35)	0.33 (0.32)
False alarm rate	0.24 (0.19)	0.55 (0.52)	0.07 (0.06)	0.13 (0.13)
Success index	0.78 (0.81)	0.68 (0.70)	0.86 (0.86)	0.74 (0.74)
FAI	0.73 (0.74*)	0.67	0.61 (0.68*)	0.66 (0.69*)

- An alternative data set for the validation of 2D flood models is presented
- Validation based on insurance claims is more conservative in specific cases because of stronger weighting to urbanized areas
- Validation approach is focused on flood exposure and loss analyses at single building scale